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Photovoltaic waste assessment in Italy

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ABSTRACT

At present, photovoltaics is, after hydro and wind power, the third most important renewable energy source in terms of its capacity to be globally installed; furthermore, for two years in a row, it was the number one new source of electricity generation installed in the European Union. Italy became the second country in the European Union concerning the cumulative installed power of PV (in 2013, the Italian PV cumulative power reached over 17,620 MW), which was also the result of the very attractive support policy.

In connection with this development, the issue has emerged about the treatment and disposal of photovoltaic waste when the operative time (approximately twenty-thirty years) of the photovoltaic systems ended. The European Union, to address this environmental impact, passed the Directive 2012/19/EU to increase the amount of waste of electrical and electronic equipment in the form of photovoltaic panels that have been appropriately collected and treated to reduce the volume that become disposed. This paper aims to provide an assessment of the potential waste arising in Italy from the use and end-of-life phases of these renewable energy systems in the coming years and their disposal and/or recycling. Based on the lifetime of 25 years of photovoltaic panels, the estimate has been referred to two periods of waste generation (2012–2038 and 2039–2050). The importance of managing this flow of waste to enhance the correct disposal of the hazardous substances as well as the importance of the recovery and recycling of valuable resources has also been underlined.

Contents

1. Introduction

Photovoltaic (PV) energy, which was used for the first time in space application technology, can be used for many applications that require electricity.

Its versatility as well as the simplicity of its installation and use have made it a popular and environmentally friendly technology. At present, PV is, after hydro and wind power, the third most important renewable energy source in terms of its capacity to be globally installed, and for two years in a row (2011 and 2012), PV was the number one new source of electricity generation installed in the European Union (EU).

The role of the EU regulation in the promotion of renewable energies, driven by the Kyoto Agreements, was relevant as was the

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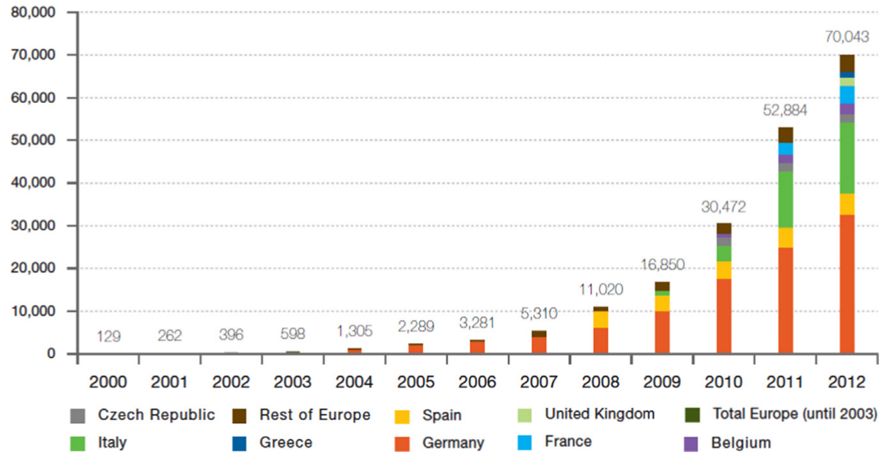

Fig. 1. Evolution of cumulative installed PV capacity in Europe (2000–2012) (MW).

reduction of the costs incurred over the years in the production, assembly and installation of PV panels. Each Member State has adopted a different support policy to compensate for the higher costs of renewable energies in order to develop these energy sources and meet the 20/20/20 renewable energy target provided by the EU Directive 2009/28/CE.

Italy has always been heavily dependent on foreign countries with regard to its energy supply. As a consequence, adequate strategies to solve the problem have been urgently needed. In the last ten years, renewable energies have been developed, particularly wind and photovoltaic ones. With reference to the last energy in 2013, its cumulative power installed reached over 17,620 MW, and the number of plants reached approximately 550,000. Since 2008, the PV power sharply increased by 3591% and the number of plants by 1315%. As a result, Italy became the second country in the European Union concerning the cumulative installed power of PV, as Fig. 1 shows [1].

With a very attractive support scheme, the Italian government has had a relevant role in the decrease of prices and consequent development of photovoltaic energy. The national support programme, called Conto Energia, started in 2005, has become much more favourable since 2007. It consists of a mix of measures, like net metering and a well-segmented feed-in tariff. From 2011 to the present, the central government policy has led to a reduction of these incentives and consequently to a decrease in the growth of these renewable energy systems.

In connection with this development, one issue that has emerged is about the treatment and disposal of the photovoltaic waste when the operative time (approximately twenty-thirty years) ends. In Italy, the new growth of these installations as a result of this concern is just beginning, compared with other countries, like Germany, where the photovoltaic energy has been widespread since more years than Italy and the quantity of the end-of-life panels is becoming a concern, although significant volumes of them will not appear until 2025. The European Union, in an attempt to address this environmental impact, passed the Directive 2012/19/EU to increase the amount of waste of electrical and electronic equipment (WEEE) [2] in the form of photovoltaic panels, which are appropriately collected and treated to reduce the amount that goes to disposal as well as to give Member States the tools to more effectively fight the illegal exportation of waste. Besides, what emerges is the importance of recycling the materials in the photovoltaic panels for many economic, environmental and social implications.

The exponential growth in the installed photovoltaic systems is what stimulated this paper, which aims to assess the potential waste arising in Italy from the use and end-of-life (EOL) phases of these renewable energy systems in the coming years as well as in their disposal and/or recycling. Thus, after a review of the European Union's regulations about this issue and the description of the main technological innovations of the sector over the years, an overview of the PV market and industry has been provided. Then, I have assessed the quality and quantity of the materials embodied in the PV systems, differentiated by various technologies, particularly those based on crystalline silicon and thin film, which are currently the main PV power systems used worldwide. Based on a lifetime of 25 years of photovoltaic panels, this assessment has been estimated with reference to two periods of waste generation (2012–2038 and 2039–2050). The conclusions of the paper underlined the importance of managing this flow of waste to ensure the correct disposal of the hazardous substances as well as the recovery and recycling of valuable resources.

2. Regulation of photovoltaic waste

As the market continues to expand and innovation cycles become even shorter, the replacement of equipment accelerates, making electrical and electronic equipment a quickly growing source of waste.

In order to manage this flow of waste, boost the recovery and recycling of electronic devices, and limit the hazardous substances, including heavy metals and others, in early 2000, the European Union passed Directives 2002/96/EC and 2002/95/EC. In December 2008, the European Commission proposed to recast the first one, and in 2012, the new Directive 2012/19/EC was passed. For the first time, the photovoltaic systems' installations at the end of the useful life are included in the list of WEEE as a result of their growth and the issue about their proper recycling and disposal.

The Directive aims to improve the collection, re-use and recycling of used electronic devices to contribute to the reduction of waste and the efficient use of resources. It also seeks to limit illegal exports of such waste from the EU and to improve the environmental performance of all operators involved in the life cycle of EEE, e.g., producers, distributors and consumers.

Moreover, the Directive establishes the producer's responsibility as a means of encouraging the design and production of EEE, which take into full account and facilitate repair, upgrading, re-use, disassembly and recycling of this equipment. It also provides for the collection, free of charge to end users, of small WEEE (no more than 25 cm), at retail shops with sales areas relating to EEE of at least 400 m^2, or in their immediate proximity.

Annex V of the Directive provides for minimum recovery of targets applicable by category and by time frame. As regards the

photovoltaic panels from 13 August 2012 until 14 August 2015, these targets are as follows: 75% shall be recovered,[1] and 65% shall be prepared for re-use and recycled. From15 August 2015 until 14 August 2018, these targets become 80% and 70%, respectively, and from 15 August 2018, these percentages will increase to 85% and 75%, respectively.

A further improvement is the harmonisation of national registration and reporting requirements under the Directive. Member States' registers for producers of electrical and electronic equipment will now have to be integrated more closely. The Commission will adopt a harmonised format to be used for the supply of information. Member States, in fact, shall ensure that the authorities responsible for implementing this directive cooperate with each other, in particular to establish an adequate flow of information to ensure that the producers comply with the provisions of this Directive and, where appropriate, provide each other and the Commission with information to facilitate the proper implementation of this Directive.

Member states shall collect information, including substantiated estimates, on an annual basis regarding the quantities and categories of EEE placed on their markets, collected through all routes, prepared for re-use, recycled and recovered within the Member State, and exported by weight on separately collected WEEEs. Member States shall, in three-year intervals, send a report to the Commission on the implementation of this directive and on this information.

The first report shall cover the period from 14 February 2014 to 31 December 2015. The Commission shall publish a report on the implementation of this Directive within nine months after receiving the reports from the Member States.

In Italy, as a consequence of the directive's provision and in accordance with the Ministerial Decree on 5 July 2012, the manufacturers of panels have to adhere to a system or consortium for panels recycling at the end of life to demonstrate the sustainability of these systems. The procedure is as follows: the national electricity organisation, which, in Italy, is called the Guarantor of Electric Services (GSE), has published information on procedures and documents to be submitted by the systems or consortia to demonstrate their suitability to the GSE requirements. After the publication of the list of suitable systems or consortia, which occurred on March 2013, manufacturers of panels used in PV plants of the 4th and 5th Conto Energia (as aforementioned, they are the national support programs), which came into operation after 1 July 2012, must provide an attestation of adhesion to a consortium or system to be granted feed-in tariffs.

Besides, to provide accessible data and information on the PV systems installed and according to Art. 7 of Decree 5th July 2012 (5th Conto Energia), an information system in support of the information regarding the certificates and declaration of photovoltaic panels and inverters, named PVCERT, was established. It aims to collect and make accessible the certificates and attestations of photovoltaic panels and inverters, particularly with regard to their quality and the identification of manufacturers and/or importers of these components into the Italian market. These documents concern, for example, details and accreditations issuing certificates and attestations by the bodies, such as testing laboratories, consortia for the recycling of panels at the end of life and certification bodies for the quality of the production process.

The main feature of the application is data uploading by the stakeholders and ensuring the validation of the data by the GSE.

3. Photovoltaic technologies

To evaluate the quantity and the quality of PV panels at the end of life, it is necessary to illustrate several available technologies.

A photovoltaic system consists of multiple components, such as cells, which are connected in series from large modules,[2] electrical and mechanical mountings and connections and tools for regulating and /or modifying the output, which is electricity.

The solar cell is the elementary building block of the photovoltaic technology. It is made of semiconductor materials, e.g., silicon, which cause the photovoltaic effect.

Sunlight can be converted into electricity just because of this effect, which was discovered by the French scientist Becquerel. When photons of light at different wavelengths strike a solar cell, they can be reflected or absorbed, or they may pass through the cell. Absorption of a photon results in the generation of an electron–hole pair, which, when separated from each other across the junction, results in the generation of a voltage, which can drive the current in an external circuit. As a result, power can be extracted from the solar cell.

There are many types of solar cells, but more than 80% of them that are currently produced worldwide consist of crystalline silicon cells. The second most used semi-conductor material is cadmium telluride, which enables the production of thin-film cells.

The range of current technologies and possible future options is grouped as listed below:

First generation: **Crystalline Silicon (c-Si)**
a) Mono crystalline
b) Polycrystalline
c) Ribbon sheets

Second generation: **Thin film**
a) Amorphous Silicon (a-Si)
b) Cadmium Telluride (CdTe)
c) Multi-junction cells (a-Si-μc Si)
d) Copper indium gallium diselenide (CIGS), copper indium diselenide (CIS)

Third generation: **Concentrator photovoltaic (CPV)** and **emerging technologies**
a) CPV
b) Dye-sensitised solar cells
c) Organic solar cells
d) Hybrid cells
e) PERC and PERL

3.1. First generation

These technologies are based on the use of two types of silicon. The first one is the mono crystalline silicon, the highest purity silicon, which is manufactured with a complex process. Thus, it is more expensive than the polycrystalline one but also much more efficient (13–19%) [3,4]. In mono crystalline silicon, the crystalline

[1] According to Waste Framework Directive 2008 definitions applicable for WEEE Directive 2012/19/EU, *'recovery'* means any operation in which the principal result is waste serving a useful purpose by replacing other materials that would otherwise have been used to fulfil a particular function or waste being prepared to fulfil that function, in the plant or in the wider economy. *'Preparing for re-use'* means checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be reused without any other pre-processing. *'Recycling'* means any recovery operation by which waste materials are reprocessed into products, materials or substances, whether for the original or for other purposes. It includes the reprocessing of organic material, but it does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.

[2] It has to be highlighted that in this paper, the term *module* is equivalent to the term *panel*, which is much more frequently used. Both of them refer to the same unit—that is, a unit composed of solar cells.

framework is homogenous, and the crystal lattice of the entire sample is continuous and unbroken with no grain boundaries.

Solar cells based on polycrystalline silicon are composed of a number of smaller crystals, and they can be recognised by a visible grain. They are the most common PV technology presently accounting for 63% of the world market because they are cheaper than the mono crystalline ones, though they have lower efficiency, in the range of 11–18% [3].

The wafer-based c-Si cells have already proven their excellent stability and reliability, operating under outdoor conditions without any deterioration in their performance. The main disadvantage is the high cost of the module price due to the low production volume at the time of manufacturing, the complex processes of cells' manufacturing and module assembly and the large amount of highly purified silicon feedstock required (approximately 15 t of feedstock for MW_p of module production). Until the early 1990s, the photovoltaic industry mainly used scraps from the microelectronics industry, so the price of feedstock was low. Over the years, the growth of the PV industry made the supply of this feedstock more and more insufficient; thus plants manufacturing solar-grade silicon with metal contamination in the order of parts per million or less were established.

The fact that the wafers have to be cut from an ingot with a wire saw is a further issue regarding wafer-based technology. It is expensive, involves significant materials losses (up to 68%) and can lead to the breaking of thin wafers. Besides, wafers have limited sizes, and they must be externally assembled. Keeping in mind these considerations, the square-shaped polycrystalline Si wafers cut from cast polysilicon ingots are more convenient to assemble than the quasi-square-shaped mono crystalline wafers.

Alternative structures, such as silicon ribbon sheets, are available, but their efficiency, at 13%, is lower than the efficiency of the first two technologies. In their manufacturing process high-temperature-resistant wires are pulled through molten silicon to form a multi-crystalline ribbon of silicon crystal. The ribbon is then cut into lengths, which are treated with traditional processes to form solar cells. The process uses less silicon (approximately half of the amount) compared to the wafer production method, but the process is thermally inefficient, so it is highly energy expensive.

3.2. Second generation

Thin-film solar cells are one or more thin layers (1–10 μm) of semiconductor materials applied to a solid and low-cost backing, e.g., stainless steel, glass or plastic [5]. Thin films greatly reduce the amount of semiconductor material required for each cell; as a consequence, their costs are reduced compared with silicon cell ones, as previously mentioned. Because of their flexibility, thin-film solar cells can double as rooftop shingles and tiles, building facades or as glazing for skylights.

Depending on the material used, four types of thin-film modules are commercially available at the moment. Amorphous silicon (a-Si) is a non-crystalline form of silicon, which has an amorphous structure. The order in atomic positions is limited to a short range. This type of thin film uses less scarce materials, and it has a cell efficiency of around 4–8% (up to 10.4% at laboratory scale) (see Table 1) [4], but it is prone to degradation.

In the second generation, the most frequently used semiconductor compound is cadmium telluride (CdTe), which is formed by cadmium and tellurium, a cost-effective material, albeit with an efficiency of up to 11%, lower than silicon. As a result, CdTe-based solar cells require a greater surface for a similar performance.

There are two concerns about this technology: the potentially negative environmental impact of high toxicity of cadmium and a possible shortage of the tellurium.

Table 1
Module efficiency (%).
Sources: [4,7,8].

Technology	Commercial efficiency	Laboratory scale efficiency
c-Si monocrystalline	13–19	25
c-Si polycrystalline	11–18	20.4
CIGS/CIS	7–12.7	20.3
CdTe	11	16.7
a-Si - μc Si	7–9.8	11.9–13.2
a-Si	4–8	10.4
CPV Multi-junction	25	25–30
Dye-sensitised solar	2–4	8–12

Technology based on a combination of a-Si and μc Si (microcrystalline), which is called tandem, has been developed in recent years. It has an efficiency of up to 9.8% (over 16.5% at the laboratory scale), but at present, it has a few shares in the PV market.

Finally, copper, indium, gallium, (di)selenide/(di)sulphide (CIGS) and copper, indium and (di)selenide/(di)sulphide (CIS) are the most promising technologies for thin-film solar cells. They present the highest efficiency (from 7% to over 12% as well as close to 20% at the laboratory scale) [4] amongst the thin films, but they incur higher manufacturing costs due to the more complex processes involved.

3.3. Third generation

The third-generation photovoltaic technologies that have developed are either currently starting to be commercialised or are still at the research level.

The concentrator photovoltaic (CPV) uses a lens to focus the sunlight onto the cells, which has been built in the concentrator collectors. The quantity of the semiconductor material used is very little, and the collection of sunlight is as much as possible because this system is designed to operate with concentrated sunlight. Its efficiency, in fact, is very high, in the range of up to 25%. However, at present, it is still expensive because of the materials utilised to manufacture the cells, such as silicon or III–IV compounds (generally gallium arsenide), which are highly efficient but quite expensive. Besides this system's higher costs, maintenance costs are also associated with it.

Dye-sensitised cells are made of certain materials, e.g., titanium dioxide, which are covered in a light-absorbing pigment, and they generally have lower costs.

The organic solar cells are composed of biodegradable materials, like organic polymers or small organic molecules; they are also of very low cost due to the low material requirements and low temperature processing, but their efficiency is only at 5%. The degradation of cells is also an issue.

Hybrid cells are involved in the combination of current technologies and are a combination of organic and inorganic semiconductors.

Other advanced technologies are the passivated emitter and rear cell (PERC) and the passivated emitter and rear locally diffused (PERL) cells [6]. The cell designs are developed in such a way that both the emitter and the rear side of the cell get passivated using a thin layer of SiO_2, so the surface passivation significantly improves the cell performance. The electricity flows through an aluminium contact that covers the rear of the wafer. These technologies demonstrate high levels of efficiency—over 20%—but at present, they are in the pre-commercial phase due to their high costs.

4. The photovoltaic market and industry

PV technology has grown over the past decade at a remarkable rate—even during difficult economic times—and is on the way to

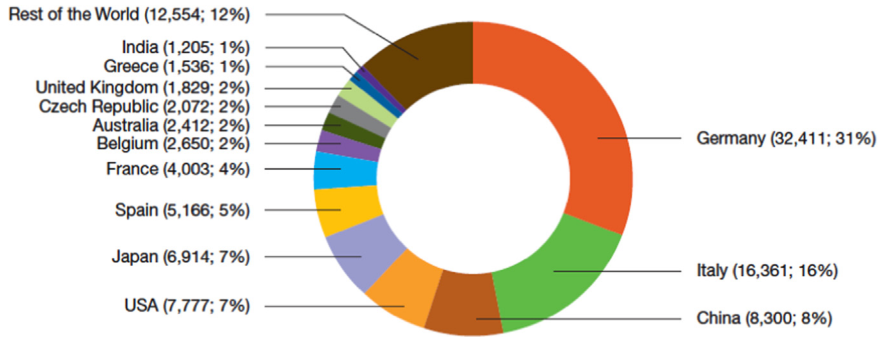

Fig. 2. Worldwide PV cumulative installed capacity share in 2012 (MW; %).
Source: [1,9].

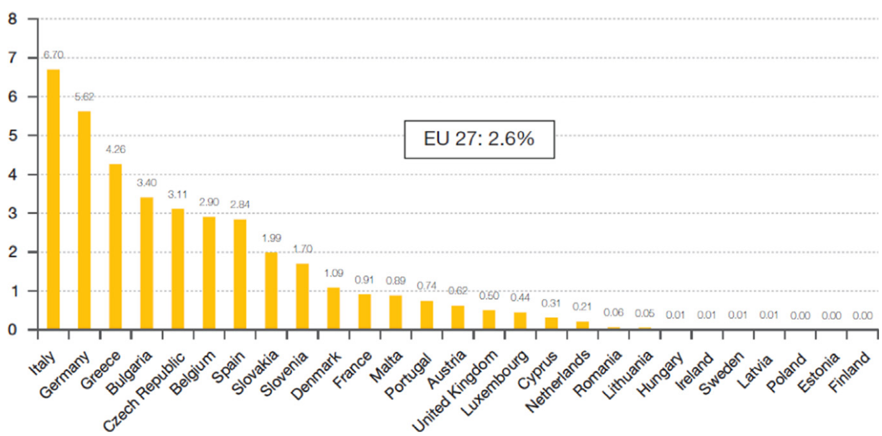

Fig. 3. PV contribution to the electricity demand in EU-27 in 2012 (based on 2012 cumulative installed capacity).
Source: [1].

becoming a major source of power generation for the world. After its record growth in 2011, the global PV market stabilised, and it experienced capacity additions in 2012 slightly above those achieved in 2011.

Worldwide, 31.1 GW of PV systems were installed in 2012, up from 30.4 GW in 2011. In Europe, 17.2 GW of PV capacity was connected to the grid in 2012, compared to 22.4 GW in 2011 and, for the first time, the PV market in Europe decreased in terms of its newly connected capacity. Europe still accounts for the predominant share of the global PV market, albeit with 55% of all new capacities in 2012, instead of 74% in the previous year.

Germany was the top market for 2012, with 7.6 GW of newly connected systems, followed by China with an estimated 5 GW, Italy with 3.4 GW, the United States with 3.3 GW and Japan with an estimated 2 GW. In 2011, a peak of installations occurred in Italy, which was the top market for the year with 9.3 MW connected. As a result, Italy and Germany accounted for over 73% of the EU market and nearly 60% of the world PV market this year.

Concerning the cumulative installed PV capacity, at the end of 2009, it was approaching 24 GW in the world, and it increased to 40.7 GW and 71.1 GW, respectively, in 2010 and 2011 [1].

In 2012, more than 100 GW of PV was installed globally, with the potential electricity production of 110 TWh every year.

Europe remains the world's leading region in terms of cumulative installed capacity, with more than 70 GW in 2012, representing 70% of the world's total PV (compared to about 75% of the world's capacity in 2011). China, the United States and Japan were the top non-European countries in 2012 with, respectively, 8.3 GW, 7.8 GW and 6.9 GW of cumulative installed capacity (see Fig. 2).

At the end of 2012, the contribution of PV systems to electricity demand in EU-27 [1], based on the capacity installed and connected to the grid, was roughly 2.6%, up from 1.15% at the end of 2010 and 2% at the end of 2011. Italy had the highest figure in the EU—that is, more than 6.7%, followed by Germany at more than 5.6%, and Greece, which reached more than 4%. Belgium, Bulgaria and other EU countries are progressing rapidly, as well (see Fig. 3). Regarding the figure of photovoltaic capacity (Wp) per inhabitant, in 2012, Germany and Italy had the highest in the EU, respectively, at 399.5 and 269 Wp/inhab, much higher than the EU average, which was 136.3 Wp/inhab.

With regard to the PV industry, the evolution of the global data of the production and demand for each region is shown in Fig. 4. Until 2003, worldwide, the situation was balanced, and production met demand; in 2004, with the booming market, Europe became a main importer, mainly from Asian countries. At present, the module production of the European PV industry is equal to only 13% of the global market and approximately 24% of its own market. The rest is imported from China and Asia-Pacific countries (APAC), which supply approximately 70% of the world's demand. It is underlined that China is the only country that has an overproduction, with 320% more than its demand. However, it is expected that this situation will change due to the local absorption of the photovoltaic production.

5. Materials and methods

An analysis of the quantity and quality of the materials in PV panels and their identification through their flows in the end-of-life

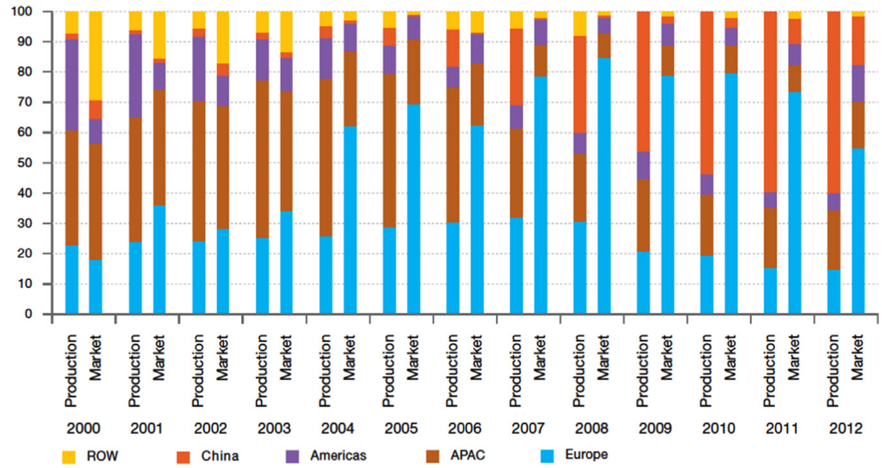

Fig. 4. PV market and production by region (2000–2012) (%).
Source: [1,9].

phase may provide clear and detailed information to help define more effective waste management strategies and to promote adequate product policies.

Thus, if the waste flow that needs to be disposed of is estimated and the materials contained in the waste are known, the composition of the mass of waste can be calculated [10]. By repeating the same calculations each year, it is possible to constantly monitor the materials that, through their commodities, transit in a given technosphere and flow as waste from the technosphere to the ecosphere. The knowledge of these data could be helpful to carry out suitable strategies to reuse or recycle the materials embodied in this equipment.

Assuming that the data from this case study can be extrapolated to the national level and considering the amount of PV panels expected to be dismantled in the coming decades, an estimate of the potential waste arising in Italy in two reference periods (2012–2038 and 2039–2050) was performed. Knowing the material composition of the PV panels, the quality of the waste can be illustrated, as well as their recycling or disposal rates.

Particularly, the crystalline silicon-based panels, which are the first-generation technologies, and the a-Si, CIGS and cadmium telluride thin film, which are the second-generation technologies, have been considered in this case study. They are currently the main PV power systems used, and their installations are the oldest ones, so they can provide an adequate data set for the calculation of waste. The paper also considers the foreseen flow of the PV concentrators and the emerging PV technologies, because their installation will occur after 2018, and it considers the flow only for the quantitative analysis, rather than the qualitative one.

It has to be underlined that poly-Si and c-Si PV panels have been grouped together for the analysis.

In the first phase of this analysis, the PV-installed systems have been expressed in terms of their power (in MW).

The lifetime of PV modules has been estimated in 25 years, on average; so it can be assumed that the installed PV power (MW) becomes waste after that period. To identify the time shifting, Table 2 shows the years of installation (x) and the years of waste generation (y), so $y=x+25$.

Particularly, two periods have been identified for the assessment: the first period includes the PV systems installed from 1987 (the year of the first installations in Italy) to 2013.[3] As a consequence, the period of WEEE production starts in 2012 (25 years after 1987) and ends in 2038 (25 years after 2013) (Table 2).

The second period refers to the years from 2014 to 2025 concerning the PV installations and consequently to the years 2039–2050 for the WEEE generation (Table 2).

With regard to the PV power data (MW), they are shown in Table 3, where the cumulative installed power (c) is the sum of annual PV Power installed (a) and the previous cumulative PV power installed (b). In the first period the installed PV power is based on historical and current data.

As regards the data of the foreseen PV power, they have been based on projections of the Italian PV installations. These projections have been calculated on the average annual growth of PV

Table 2
Years of PV installations and waste generation.

Years of installations (x)	Years of waste generation (y)
$y=x+25$	
1987	2012
1992	2017
1997	2022
1998	2023
1999	2024
2000	2025
2001	2026
2002	2027
2003	2028
2004	2029
2005	2030
2006	2031
2007	2032
2008	2033
2009	2034
2010	2035
2011	2036
2012	2037
2013	***2038***
2014	2039
2015	2040
2016	2041
2017	2042
2018	2043
2019	2044
2020	2045
2021	2046
2022	2047
2023	2048
2024	2049
2025	***2050***

[3] It has to be underlined that for the first ten years (from 1987 to 1997), the data are cumulatively illustrated for each five years, due to the low amount of PV installations and uncertainties of data; from 1998, the data are referred to each year.

systems, according to the estimated following rates: 17.3% for 2014 and 2015, 8% up to 2020 and 12.5% from 2021 to 2025 [13,15].

To share the photovoltaic power data per technology, the historical trends and projections of the shares of the four types of PV technologies installed in Italy are illustrated in Fig. 5. It must be stressed that these percentages are different from the EU ones. Particularly, the c-Si technology has been the main one in Italy for a longer time: for example, in 2010, it accounted for 91% in Italy and only for 80% in the EU. Instead, from 2020, Italian and EU data for all of the PV technologies will be considered to be equivalent.

Table 3
Annual and cumulative PV power installed in Italy (1987–2025) (MWp).
Source: [11–14].

Years of PV installations	Annual PV power installed (a)	Previous cumulative PV power installed (b)	Cumulative PV power installed (c)
	c=a+b		
1987	6	0	6
1992	3	6	9
1997	8	9	17
1998	1	17	18
1999	1	18	19
2000	1	19	19
2001	1	19	20
2002	2	20	22
2003	4	22	26
2004	5	26	31
2005	7	31	38
2006	13	38	50
2007	37	50	87
2008	345	87	432
2009	712	432	1144
2010	2326	1144	3470
2011	9492	3470	12,962
2012	3458	12,962	16,420
2013	1204	16,420	17,624
2014	3049	17,624	20673
2015	3576	20,673	24,249
2016	1940	24,249	26,189
2017	2095	26,189	28,284
2018	2263	28,284	30,547
2019	2444	30,547	32,991
2020	2639	32,991	35,630
2021	4454	35,630	40,084
2022	5011	40,084	45,095
2023	5637	45,095	50,731
2024	6341	50,731	57,073
2025	7134	57,073	64,207

Data of Fig. 5 have been used to identify the share of the installations (MW) per technology and per year of production waste, as Table 4 illustrates.

Then, it is necessary to transform the MW of the PV installations in mass (kg/W), which will be different per individual

Table 4
Waste production (MW) shared per technology.
Source: Personal elaboration by the author.

Years	c-Si	a-Si	Cd-Te	CISG	Emerging-CPV
2012	6	0	0	0	0
2017	3	0	0	0	0
2022	8	0	0	0	0
2023	1	0	0	0	0
2024	1	0	0	0	0
2025	1	0	0	0	0
2026	0.97	0.03	0	0	0
2027	1.9	0.1	0	0	0
2028	3.9	0.1	0	0	0
2029	4.5	0.2	0	0	0
2030	6.5	0.3	0	0	0
2031	11.9	0.4	0.3	0	0
2032	34.8	1.5	0.7	0	0
2033	320.5	10.3	13.8	0	0
2034	655	21	36	0	0
2035	2117	70	116	23	0
2036	8828	190	380	95	0
2037	3251	35	138	35	0
2038	*1084*	*24*	*72*	*24*	0
2039	2683	61	305	0	0
2040	3004	143	358	72	0
2041	1533	58	291	58	0
2042	1529	84	377	105	0
2043	1584	113	362	158	45
2044	1637	171	318	196	122
2045	*1610*	*211*	*290*	*369*	*158*
2046	2717	356	490	624	267
2047	3056	401	551	701	301
2048	3438	451	620	789	338
2049	3868	507	698	888	380
2050	*4352*	*571*	*785*	*999*	*428*

Table 5
Crystalline Silicon panels specifications.
Source: [15,16].

Total weight per panel (kg)	22
Power (Wp)	215

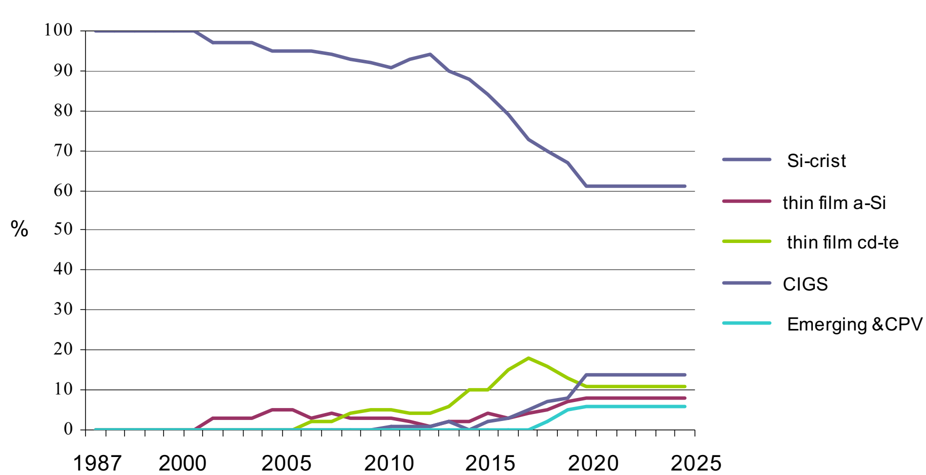

Fig. 5. Shares of PV technology used in Italy and future estimates (%).
Source: Personal elaboration by the author on data [15,4].

Table 6
Thin-film specification by technology.
Source: [15,17,18].

Type	*Manufacturer*	*Model*	*Wp*	*kg*	*kg/Wp*
a-Si	Trony Solar	TRM50A	50.0	19.5	0.390
	Xsol	GTS-85/90	90.0	25.0	0.278
	Kaneka	G-EA060	60.0	13.7	0.228
	Golden Sun Solar (GS solar)	GS 50–55	55.0	14.4	0.262
	Polar Photovoltaics	TFSM-T-X	52.0	13.7	0.263
Average					0.284
CdTe	First Solar	FS CTS-265	65.0	12.0	0.185
	First Solar	FS CTS-267	67.5	12.0	0.178
	First Solar	FS CTS-270	70.0	12.0	0.171
	GE Energy	GE CdTe	83.0	13.0	0.157
	Antec Solar	ATF-50	50.0	16.0	0.320
Average					0.202
CIS/CIGS	Sulfurcell	SCG60-HF-F	60.0	14.6	0.243
	Global solar	PN33060-O	60.0	9.0	0.150
	Würth Solar	WSK0021	55.0	9.7	0.176
	Würth Solar	WSG0035 E075	75.0	12.7	0.169
	Axun Tek Solar	Facade	80.0	15.0	0.188
Average					0.185

Table 7
Weight (kg per Watt) per technology.

Technology	Average weight (kg/Wp)
c-Si	0.102
a-Si	0.284
CdTe	0.202
CIGS	0.185
Emerging technology/CPV	0.1

technology, to estimate the quantities of PV installations as well as the related waste.

Some details about the Wp (Watt-peak), a typical measure of the nominal power of a PV installation under a defined illumination (a light intensity of 1000 W/m^2 at a temperature of 25 °C), have been identified to determine the weight of PV panels and the composition for the weight by type of technologies. This unit allows for the comparison of different panels. Generally, the standard crystalline silicon panels contain between 60 and 72 solar cells and have a nominal power from 120 to 300 Wp (with an average of 215 Wp), depending on their efficiency and size. The weight of this type of PV panel is in the range of 5–28 kg (with an average of 22 kg) (see Table 5). Standard thin-film panels, particularly a-Si, CdTe and CIS/CIGS, have lower nominal power (from 60 to 120 Wp). Modules can be sized according to the site where they will be placed. The total weight per module is consequently different per technology considered as well as the efficiency, design and electrical characteristics of each one. Thus, of a selected list of thin films, commercially available in the last years (from 2006 onwards), five models per technology have been considered (Table 6). It must be stressed that forcing the grouping of unlike models between the three technologies was required, but it was necessary to calculate an average of the indicators for each technology. Particularly, the average data of the total weight and power for the different types of thin films modules were assumed, as Table 6 illustrates.

Thus, on the basis of the data of Tables 5 and 6, the weight (kg) per Watt and technology are each summarised in Table 7.

Then, by taking into account the annual installation of the PV panels shared from different technologies used (Table 4) and the weight per technology (Table 7), over the above-mentioned number of years, the quantity of waste each year and the total mass at the end of a given period can be estimated for each technology considered, according the following equation:

$$w_y = \sum_{x=1}^{y} u_x w \tag{5.1}$$

u_x=MW/year
w=weight (t) per MW
x=year
y=year of waste generation (x+25)

Then, knowing the material composition of the modules, it is possible to illustrate the quality of the waste and the share of each material embodied in the different types of PV modules, as Table 8 shows. Regarding the composition of the photovoltaic panels, there is extensive information about the technologies currently on the market, as mentioned above, and there are few data for the emerging ones, which are currently under development [15]. Therefore, the total mass of each material fraction per year and the entire period considered only for the silicon-based technologies and for thin films (a-Si, cd-Te and CIGS) have been calculated, according to the data in Table 8 and the amount of waste generated per technology.

Another consideration is about the recovery and recycling of the materials embodied in the photovoltaic panels.

The composition of thin-film modules requires special processing technologies to manage their recycling. There are already technologies in existence to recycle thin-film modules, e.g., the company First Solar operates a qualified, industrial-scale recycling process using chemical extraction, which is typical amongst similar industrial processes [22]. Alternative methods are being explored to further reduce the cost of recycling and to develop methods to reuse semiconductor materials, especially ones that have economic value, such as tellurium and indium for CdTe and CIS.

The average rate of recycling for the materials of the PV modules, primarily glass and aluminium, is extremely high, at 95% and 100%, respectively.

Generally, in the case of crystalline silicon panels, the total recovery and recycling are approximately equal to 90%, and waste incineration with energy recovery is equal to 10% (e.g., polymers). The last percentage has to be referred to EVA and films that are typically removed from PV cells by using organic solvents and/or by thermal decomposition (e.g., pyrolysis at approximately 500 °C) [23].

Regarding the rare metals, particularly indium, silver, germanium and gallium, altogether, they are only equal to approximately 1% of the mass of the PV panel, but their value is significant [24]. As a consequence, they have to be recycled, even if their recycling rate is around 30%. Other materials for which recovery is important, particularly due to their shortages, are copper and tellurium.

According to the recycling rates of Table 9, the quantities of the materials recovered have been calculated.

Concerning hazardous substances, like lead and cadmium, their controlled disposal is aimed to avoid negative impacts on the environment and human health.

6. Results

To quantify the yearly and cumulative amount of PV waste, Eq. (5.1) has been used for each technology considered.

These data have been illustrated in the second column of Tables 10–14. It has to be underlined that the figures in the last tables are referred year by year up to 2038, and the ones from 2039–2050 are grouped into two years: 2045, which represents the sum of the years 2039–2045, and 2050, which is the sum of the years 2046–2050.

Table 8
Average material composition of PV modules per technology (%).
Source: [15,19–21].

Proportion in %	c-Si	a-Si	CdTe	CIGS
Glass	74.16	86	95	84
Aluminium	10.30	0.035	0.35	12
Polymers (e.g. EVA)	6.55		3.5	3
Backing film (Tedlar)	3.60			
Adhesive (e.g. silicone). potting compound. hot melt glue	1.16	0.02		
Polyol/MDI (Methylene diphenyl diisocyanate)		12		
Copper	0.57	0.9	1	0.8
Silver	0.004–0.006			
Tin	0.12	0.043		
Zinc	0.12		0.01	0.12
Silicon	3.35	0.0064		
Lead	0.06			0.05
Cadmium			0.07	0.0005
Tellurium			0.07	
Indium		0.5		0.02
Selenium				0.03
Gallium				0.01
Germanium		0.5		

Table 9
Recovery rate of materials.
Source: [15,25–27].

Glass	95% *(purity 99.99975)*
Aluminium	100%
Silicon	76–86% *(purity: 59% > 99.9999 41% > 99.995)*
Tellurium	80–95% *(purity 99.7%)*
Copper	78–100%
Silver	30–50%
Indium. Gallium. Germanium	~20–40%

Table 10
Amount of waste generated per c-Si technology and their composition (t).

Years of waste production	Tons	Waste composition										
		Glass	Frames (Aluminium)	EVA	Backing film (Tedlar)	Adhesive, potting compound	Silicon	Copper	Tin	Lead	Zinc	Silver
2012	*563*	417	58	37	20	7	19	3	1	0	1	0
2017	*307*	228	32	20	11	4	10	2	0	0	0	0
2022	*839*	622	86	55	30	10	28	5	1	1	1	0
2023	*102*	76	11	7	4	1	3	1	0	0	0	0
2024	*82*	61	8	5	3	1	3	0	0	0	0	0
2025	*51*	38	5	3	2	1	2	0	0	0	0	0
2026	*99*	74	10	6	4	1	3	1	0	0	0	0
2027	*198*	147	20	13	7	2	7	1	0	0	0	0
2028	*397*	294	41	26	14	5	13	2	0	0	0	0
2029	*457*	339	47	30	16	5	15	3	1	0	1	0
2030	*661*	490	68	43	24	8	22	4	1	0	1	0
2031	*1215*	901	125	80	44	14	41	7	1	1	1	0
2032	*3558*	2639	366	233	128	41	119	20	4	2	4	0
2033	*32,785*	24,313	3377	2147	1180	380	1098	187	39	20	39	2
2034	*67,048*	49,723	6906	4392	2414	778	2246	382	80	40	80	3
2035	*216,534*	160,582	22,303	14,183	7795	2512	7254	1234	260	130	260	11
2036	*903,059*	669,709	93,015	59,150	32,510	10,475	30,252	5147	1084	542	1084	45
2037	*332,528*	246,603	34,250	21,781	11,971	3857	11,140	1895	399	200	399	17
2038	*110,852*	82,208	11,418	7261	3991	1286	3714	632	133	67	133	6
Total (2012–2038)	*1,671,336*	*1,239,463*	*172,148*	*109,473*	*60,168*	*19,387*	*55,990*	*9527*	*2006*	1003	*2006*	*84*
2045	1,389,286	1,030,295	143,096	90,998	50,014	16,116	46,541	7919	1667	834	1667	69
2050	1,783,268	1,322,472	183,677	116,804	64,198	20,686	59,739	10,165	2140	1070	2140	89
Total (2012–2050)	*4843891*	*3,592,229*	*498,921*	*317,275*	*174,380*	*56,189*	*162,270*	*27,610*	*5813*	*2906*	*5813*	*242*

Table 15 shows the total amount of the waste generated in the period 2012–2038, which is equal to 1,957,099 t, corresponding to the photovoltaic installations from 1987 to 2013, and the estimated amount during the period 2039–2050, which is 6,281,868 t, corresponding to the installations during 2014–2025. Then, in 2050, the grand total of photovoltaic waste installed in the period 1987–2025 is equal to 8,238,967 t.

The most important waste stream in 2050 to be expected are c-Si panels at 4,843,891 t (58.7%), followed by thin-film panels (38.7%) with 3,191,037 t, of which the CdTe technologies is around

Table 11
Amount of waste generated per a-Si technology and their composition (t).

Years of waste production	Tons	Waste composition								
		Glass	Cable (Cu)	Aluminium	Silicon	Polyol /MDI	Tin (oxide /bioxide)	Hot melt glue	Indium	Germanium
2012	0	0	0	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0	0	0	0
2022	0	0	0	0	0	0	0	0	0	0
2023	0	0	0	0	0	0	0	0	0	0
2024	0	0	0	0	0	0	0	0	0	0
2025	0	0	0	0	0	0	0	0	0	0
2026	9	7	0	0	0	1	0	0	0	0
2027	17	15	0	0	0	2	0	0	0	0
2028	34	29	0	0	0	4	0	0	0	0
2029	67	57	1	0	0	8	0	0	0	0
2030	97	83	1	0	0	12	0	0	0	0
2031	107	92	1	0	0	13	0	0	1	1
2032	420	361	4	0	0	50	0	0	2	2
2033	2936	2525	26	1	0	352	1	1	15	15
2034	6070	5220	55	2	0	728	3	1	30	30
2035	19,818	17,043	178	7	1	2378	9	4	99	99
2036	53,915	46,367	485	19	3	6470	23	11	270	270
2037	9821	8446	88	3	1	1178	4	2	49	49
2038	6839	5881	62	2	0	821	3	1	34	34
Total (2012–2038)	*100,147*	*86,126*	*901*	*35*	*6*	*12,018*	*43*	*20*	*501*	*501*
2045	238,953	205,500	2151	84	15	28,674	103	48	1195	1195
2050	649,261	558,365	5843	227	42	77911	279	130	3246	3246
Total (2012–2050)	*988,362*	*849,991*	*8895*	*346*	*63*	*118,603*	*425*	*198*	*4942*	*4942*

Table 12
Amount of waste generated per CIGS technology and their composition (t).

Years of waste production	Tons	Waste composition									
		Glass	Aluminium	Polymers e.g. EVA	Zinc	Lead	Copper	Indium	Selenium	Gallium	Cadmium
2012	0	0	0	0	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0	0	0	0	0
2022	0	0	0	0	0	0	0	0	0	0	0
2023	0	0	0	0	0	0	0	0	0	0	0
2024	0	0	0	0	0	0	0	0	0	0	0
2025	0	0	0	0	0	0	0	0	0	0	0
2026	0	0	0	0	0	0	0	0	0	0	0
2027	0	0	0	0	0	0	0	0	0	0	0
2028	0	0	0	0	0	0	0	0	0	0	0
2029	0	0	0	0	0	0	0	0	0	0	0
2030	0	0	0	0	0	0	0	0	0	0	0
2031	0	0	0	0	0	0	0	0	0	0	0
2032	0	0	0	0	0	0	0	0	0	0	0
2033	0	0	0	0	0	0	0	0	0	0	0
2034	0	0	0	0	0	0	0	0	0	0	0
2035	4303	3615	516	129	5	2	34	1	1	0	0
2036	17,560	14,751	2107	527	21	9	140	4	5	2	0
2037	6397	5374	768	192	8	3	51	1	2	1	0
2038	4455	3742	535	134	5	2	36	1	1	0	0
Total (2012–2038)	*32,715*	*27,481*	*3926*	*981*	*39*	*16*	*262*	*7*	*10*	*3*	*0*
2045	177,208	148,854	21,265	5316	213	89	1418	35	53	18	1
2050	740,135	621,713	88,816	22,204	888	370	5921	148	222	74	4
Total (2012–2050)	*950,058*	*798,049*	*114,007*	*28,502*	*1140*	*475*	*7600*	*190*	*285*	*95*	*5*

39% (1,252,617 t) (Fig. 6). The emerging and CPV technologies are expected to be only 0.6%, equal to 204,040 t.

It is highlighted that up to 2038, the share of c-Si waste panels, equal to 85.4%, is much higher than the share of the total period, followed by the CdTe with 7.8%, a-Si (over 5%) and CIGS of 1.7%. In the second period, 2039–2050, the situation will change, and the c-Si will account only for 50.5%, the CdTe for 17.5%, followed by CIGS (14.6%), a-Si (14.1%) and the emerging and CPV technologies, the share of which is equal to 3.2%.

The material composition shown in Table 8 and the quantities, which have already been calculated, allow us to evaluate the quality of the PV waste per technology and period considered, as illustrated in Tables 10–13. As already highlighted, the analysis of the waste from the photovoltaic emerging technologies and CPV is only related to the quantities of waste, rather than to the quality of the same.

For all technologies considered, glass is the most frequently used material, followed by aluminium and polymers.

Particularly, for the primary representative technologies in 2050, which are c-Si panels and CdTe thin film, Tables 10 and 13 show the following results: the 4,843,891 t of c-Si mainly consist of 3,592,229 t of glass, 498,921 t of aluminium, 317,275 t of EVA and others, of which 27,610 t is copper, 242 t is silver and 162,270 t is silicon. Concerning the CdTe thin film, in 2050, the 1,252,617 t should be disposed of. The quantity of this will include 1,189,986 t of glass, 877 t of cadmium, 877 t of tellurium, together with 12,526 t of copper.

Table 13
Amount of waste generated per CdTe technology and their composition (t).

Years of waste production	Tons	Waste Composition						
		Glass	Polymers (e.g. EVA)	Cadmium	Tellurium	Aluminium	Copper	Zinc
2012	0	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0	0
2022	0	0	0	0	0	0	0	0
2023	0	0	0	0	0	0	0	0
2024	0	0	0	0	0	0	0	0
2025	0	0	0	0	0	0	0	0
2026	0	0	0	0	0	0	0	0
2027	0	0	0	0	0	0	0	0
2028	0	0	0	0	0	0	0	0
2029	0	0	0	0	0	0	0	0
2030	0	0	0	0	0	0	0	0
2031	51	48	2	0	0	0	1	0
2032	149	142	5	0	0	1	1	0
2033	2784	2645	97	2	2	10	28	0
2034	7195	6835	252	5	5	25	72	1
2035	23,493	22,318	822	16	16	82	235	2
2036	76,695	72,861	2684	54	54	268	767	8
2037	27,941	26,544	978	20	20	98	279	3
2038	14,592	13,863	511	10	10	51	146	1
Grand Total (2012–2038)	*152,901*	*145,256*	*5352*	*107*	*107*	*535*	*1529*	*15*
2045	464,743	441,506	16,266	325	325	1627	4647	46
2050	634,973	603,224	22,224	444	444	2222	6350	63
Grand Total (2012–2050)	*1,252,617*	*1,189,986*	*43,842*	*877*	*877*	*4384*	*12,526*	*125*

Table 14
Amount of waste generated per emerging technology and CPV (t).

Years of waste production	Tons
2012	0
2017	0
2022	0
2023	0
2024	0
2025	0
2026	0
2027	0
2028	0
2029	0
2030	0
2031	0
2032	0
2033	0
2034	0
2035	0
2036	0
2037	0
2038	0
Grand Total (2012–2038)	*0*
2045	32,580
2050	171,460
Grand Total (2012–2050)	*204,040*

Then, keeping in mind the recovery and recycling rates of the main materials indicated in Table 9, their averages have been applied to the total of each of the materials, which is the sum of the subtotals of each material for each type of PV panel waste stream generated in 2050. This has been calculated and illustrated in Table 16. It must be stressed that in this analysis, a collection rate[4] of the end of the life of the PV panels equal to 100% has been considered, due to the need for the assessment of the entire flow of this waste.

[4] Despite existing regulations, only 20–40% of e-waste in the EU is collected and treated in the existing recycling lines, but low concentration metals are often not recovered, and have significant environmental impacts when disposed of in landfills or incinerators.

Table 15
Yearly and cumulative waste production (2012–2050) (t).

Years	Tons
2012	563
2017	307
2022	839
2023	102
2024	82
2025	51
2026	108
2027	216
2028	431
2029	524
2030	757
2031	1372
2032	4128
2033	38,505
2034	80,313
2035	264,148
2036	1,051,230
2037	376,687
2038	*136,738*
Total (2012–2038)	*1,957,099*
2039	353,386
2040	433,434
2041	242,856
2042	275,824
2043	301,128
2044	328,642
2045	367,501
2046	620,158
2047	697,678
2048	784,888
2049	882,999
2050	*993,374*
Total (2038–2050)	*6,281,868*
Grand Total (2012–2050)	***8,238,967***

The materials considered for this analysis, the totals of which are shown in Table 16, represent approximately 88% of the total amount. The remaining part (about 10%) is EVA and polymers that are separated and/or incinerated with energy recovery.

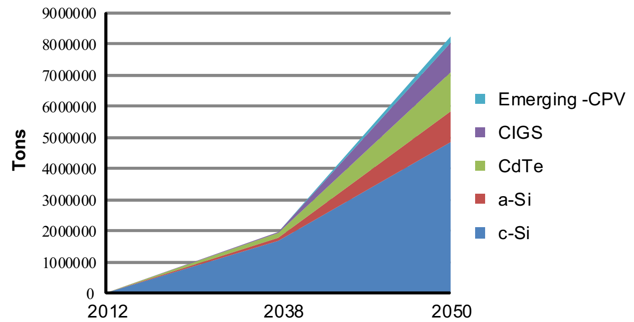

Fig. 6. Amount of Italian estimated waste generated per technology (2012–2050) (t).

Table 16
Materials recovered (t) from PV waste flow generated up to 2050.

Material	Waste (t)	Recovery rate (%)	Waste recovered (t)
Glass	6,430,255	*95*	6,108,742
Aluminium	617,658	*100*	617,658
Silicon	162,334	*81*	131,490
Tellurium	877	*87.5*	767
Copper	56,632	*89*	50,403
Silver	242	*40*	97
Indium	5132	*30*	1540
Gallium	95	*30*	29
Germanium	4942	*30*	1483

Other materials, particularly cadmium and lead, constitute only 0.052% of the total waste in 2050, but they are very hazardous ones; below, their leaching has been discussed.

Cadmium and lead, which are especially contained, respectively, in thin-film CdTe and crystalline silicon panels, have negligible leaching if they remain at the same pH as the panels themselves, while exposure to low pH, like nitric acid or rain (for instance, in the landfill setting), increases leaching of these heavy metals. The cadmium leaching is in the range of 29–40% of its average content in thin film [15]. Then, considering that 877 t of cadmium is embodied in CdTe thin films, which end their lives in 2050, its potential leaching is between 254 t and 351 t.

The leaching of lead, from 13–90%, can be calculated in the same mode, considering that the quantity of lead in c-Si and CIGS in 2050 is 3381 t, so the relative value's results range from 439.5 t to 3043 t.

7. Discussion

The assessment of the photovoltaic panels at the end of life allows for the identification of adequate policies to monitor and manage a relevant flow of waste that will became a reality in the short term. The knowledge both of the quantity and quality of the waste discussed in this analysis can be fit to different periods, from the yearly to the medium and the long term. It can also be adjusted for materials and/or groups of materials as well as levels—from national to international ones.

According to the new WEEE directive provisions, illustrated in Section 2, recovery and recycling must be equal to 75% and 65%, respectively. Keeping in mind the composition of the standard PV panels, both c-Silicon and thin films, on average, 80% of them are made from glass, so the recovery and the recycling of this material alone is enough to reach the Directive targets. Then, the increase in the recovery and recycling shares provided for since 2018 will have great relevance to enhance the management of the end of life of these waste materials.

Although quantities of these recovered materials may appear very small compared with the global consumption of the same raw materials, the situation changes if these quantities are compared with the consumption of these materials in only the PV sector. If the correlation between the raw materials and the recycled materials is applied in every manufacturing sector, it would be possible to aim to close the materials circulation loop. For example, the material flow analysis concerning the CdTe modules shows that the tellurium recycled from end-of life modules (together with recycled Te from photovoltaic production scrap) can constitute a significant share of the feedstock and in the best case, these flows, together with more material efficiency measures on the module and the process, can reduce the primary tellurium demand to below zero by 2038 [26]. This is very important for the shortage of this rare metal.

It should be noted that the increase in the consumption of these commodities is leading to overexploitation of natural capital. The rate of utilisation of natural resources is faster than their rate of regeneration, especially given that the volume of non-renewable resources used is too high compared with the reserves still available. This disparity creates the need to reduce the use of primary resources —both energy and material inputs, such as copper ore or tellurium. In the case of copper, for instance, in 2012, the global refined copper demand exceeded production by about 400,000 t, the third consecutive year of production deficit [28].

In addition, the copper concentration in PV waste is equal to or slightly lower than that of copper ore: sulphide ores contain copper at levels most often below 1%, and many process steps are required to obtain 99.99% copper metal from them [29].

The increase in the recycling of some metals, like copper, may prove to be economically worthwhile for Italy, which does not have copper mines and meets its domestic demand (approximately 1 Mt) by importing (61.4%) and recycling (38.6%). The recovery of this metal from PV waste, although in small quantities each year, may represent a valuable contribution. Additionally, in the case of aluminium, Italian production from recycling scraps was equal to 860,000 t in 2012; thus, the quantity of aluminium recoverable by the PV waste allows for significant reduction in economic and environmental costs.

A particular consideration has to be made about the rare metals present in PV panels. These are valuable, and according to the recovered quantities indicated in Table 16 and to their price projections in 2050 (silver at 1348 €/kg, indium at 773 €/kg, gallium at 754 €/kg and germanium at 1163 €/kg), the value of these metals could be estimated [15]. It is equal, respectively, to 130 million euros, 1.2 billion euros, 21.5 million euros and 1.7 billion euros, and could contribute to increase the benefits of the recovery and recycling phases.

The methodology used in this paper can also be used to quantify and plan for the correct disposal of some hazardous substances, such as lead and cadmium. They can be very harmful due to their potential leaching from the photovoltaic panels, and when incorrectly disposed of, this could present environmental and health risks. Ecosystems close to lead sources can lose biodiversity and experience decreased growth and reproductive rates in plants and animals and other effects. In humans, this heavy metal is linked with issues of reproductive and nervous systems in the foetus and young as well as cardiovascular problems and osteoporosis in the elderly.

Cadmium is another heavy metal that accumulates in living organisms and has a biological half-life of 30 years. Additionally, severe illnesses associated with low-level cadmium poisoning can have a latency of up to 10 years. In humans, its accumulation can cause carcinomas and serious pathophysiological changes.

It is possible to estimate the external costs of lead and cadmium leaching. Its cost (euros/kilogram) is linked to soil

pollution for lead and to air pollution for cadmium. Both values consider only damages to human health and not ones to the environment. Considering that these costs are equal to 1174 €/kg for lead and 46 €/kg for cadmium [30], it is possible to calculate that in 2050, the improper disposal of 3381 t of lead mainly contained in c-Si panels (average leaching 1741.2 t, according to the data above calculated) and 877 t of cadmium (average leaching 302.5 t), mainly contained in CdTe thin film, respectively, will cost over 2 billion euros and nearly 14 million euros.

8. Conclusion

This exponential growth of photovoltaic energy will create a large potential amount of electronic waste (e-waste) in the coming decades and, at the same time, a rising consumption of resources (such as energy, water and chemical substances) to manufacture new PV modules [31].

In most cases, there is a decoupling between the space and time of the environmental and economic effects between the production and consumption of these equipment, because they are carried out in different countries, often far apart, as illustrated in the section about the photovoltaic industry and market.

Hence, inputs with high values, such as metals and rare metals, are used in some nations and produce photovoltaic waste in others, such as Italy, due to disposal difficulties. Therefore, a global policy is required to establish and monitor suitable environmental and economic strategies to avoid distorting effects.

Based on these considerations, appropriate end-of-life management of these wastes would most likely enable the efficient recovery of valuable materials whose recycling, in other production processes, could prevent their depletion. Additionally, it can allow for the correct disposal of those hazardous substances, like cadmium and lead. It is important to monitor this flow to facilitate better e-waste management practices.

In this direction, it is important to stress the necessary reduction of the content of these substances just in the production chain along with the opportunity to stimulate the ecological design of the PV systems to enhance the appropriate treatment of waste PV modules and to guarantee the highest economically feasible collection and recovery rates. For example, the a-Si amorphous silicon products could be recycled through standard glass recovery and recycling processes. The greater challenge with a-Si cell recycling is that they are often embedded in products and end up being disposed of in the household waste stream. Thus, the challenge with recycling this specific PV technology would entail changing consumer habits, but it would also be to stimulate the industries to create better designs suitable for recycling.

The assessment of PV waste, as was done in this paper, can be employed as a strategic tool to promote the protection of the climate and the environment in enhancing increased and sustainable use of PV technology, create a positive environment for the ongoing growth of the PV industry and install an overall waste management policy. The expected further growth of PV energy calls for planning for the suitable monitoring and management of resources, both in the end-of-life phase and in the production phase.

This growth could potentially lead to constraints in material supply. At present, indeed, there are many contradictions in the production phase, which cause environmental and economic impacts on this sector. For instance, despite their higher energy intensity for production, the use of virgin, raw materials in photovoltaic panel production has been considered less expensive, instead of recycled materials, for example in the case of silicon-based panels due to the virtually unlimited supply of silicon as a raw material. As a consequence the huge increase of c-Si PV technology in the last few years has already led to the shortage in production. Besides the competitive markets, particularly the electronic one, is the need of high-purity silicon, which increases the economic pressure and results in production bottleneck for solar-grade silicon. The cumulative silicon demand can be reduced due to the recycling. According to the estimates in 2040 the demand will reduce from 17 Mt to 13.4 Mt and there will be a surplus of silicon metal-based solar panels recycling by 2040 [32].

For CIS, CIGS and CdTe thin films, however, there are more potential economic incentives to enhance the recycling phase due to the rarity of tellurium, indium and other rare metals, particularly in comparison to the expected future growth in the PV industry and the related exponential growth in raw material demand [33,34].

It has to be underlined that in Italy, the issue concerning this waste flow is in the starting phase, while in Germany, nowadays, there is a great amount of PV waste to manage. Beginning in 2033, as illustrated, the flow of PV panels at the end of life in Italy will significantly increase. Thus, from now on, all initiatives—both voluntary and mandatory ones—which engage all stakeholders, will play a fundamental role in managing this sector.

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